Journal of Wind Engineering and Industrial Aerodynamics, 36 (1990) 75-86
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

DOWNBURSTS: Meteorological Features and Wind Field Characteristics

T. Theodore Fujita *

ABSTRACT

Since the term "downburst" was coined by the author back in 1976, it has been subclassified into "microburst" and "macroburst" according to the horizontal dimension of the wind system. Introduced in this paper is the basic observational evidence of the microburst investigated by three fact-finding projects in 1978, 1982, and 1986, at three different climatological locations in the United States. Described briefly are the three major aircraft accidents in microbursts and some examples of the wind damage by strong microbursts. Current estimates of the maximum microburst wind at the 10^{-5} per year probability is as high as 150 mph, which could result in the tornado-like damage.

* Professor of Meteorology, Department of Geophysical Sciences
University of Chicago, Chicago, IL 60637, U.S.A.

0167-6105/90/$03.50

INTRODUCTION

Unlike large-scale tropical and continental cyclones, severe local storms intensify very rapidly and dissipate after causing storm damage. The tornado, the worst severe local storm on earth, is characterized by a fast-rotating column of rising air which originates on or near the ground where the air swirls and converges at high speed.

The microburst is an anti-tornado storm, consisting of a slow-rotating column of descending air which, upon reaching the ground, bursts out violently. Until the microburst winds were identified by the author, a number of fatal aircraft accidents occurred in microbursts during takeoff and landing operations at low altitudes. Because the microburst windspeed at low probability could reach the damage-causing intensity, some wind damage classified as tornado damage in early years could have been caused by strong microburst winds. The highest microburst wind ever recorded by an anemometer scaled off at 150 mph.

DISCOVERY OF DOWNBURST

A thunderstorm is a local storm produced by a cumulonimbus cloud and always accompanied by lightning and thunder. A severe thunderstorm induces strong gusty winds, heavy rain, hail, and sometimes tornadoes. Because cumulonimbus clouds rise vertically to the tropopause and often beyond, thus overshooting into the stratosphere, meteorologists in early days thought that thunderstorms consist of strong currents of rising air.

A number of aircraft accidents occurred in thunderstorms during the Second World War. In revealing the structure of thunderstorms, Byers and Braham (1949) operated the Thunderstorm Project, 1946 in Florida, and 1947 in Ohio. They found that a thunderstorm evolves in three stages. The storm in the growing stage is characterized by rising currents. In the mature stage however, both rising and sinking currents coexist inside the cloud and a tornado could occur in this stage. During the dissipating stage, the cloud is dominated by sinking currents until the cloud breaks up. These rising and sinking currents were called the "updraft" and the "downdraft", respectively.

Because a downdraft, no matter how strong while in cloud, must slow down to zero upon reaching the ground, meteorologists thought that nobody on the ground can be affected by a descending downdraft. Since the 1960s, the author conducted aerial photographic missions after tornadoes, obtaining numerous pictures of damage left behind by all types of tornadoes (see Fig. 1). After 15 years of experience, the author was able to identify the tornado damage almost immediately while flying over the storm's path.

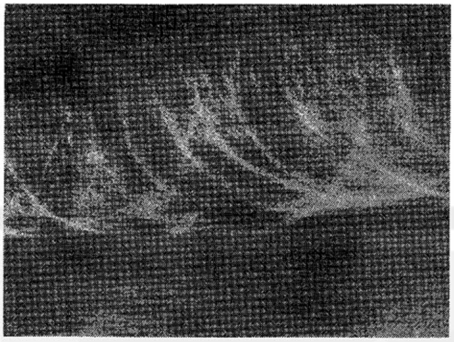
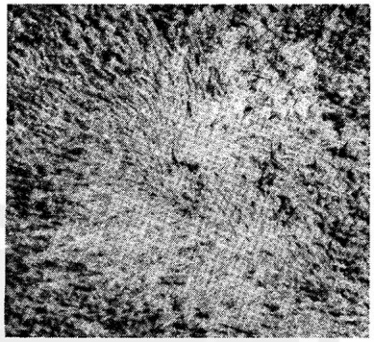

Fig. 1. Aerial views of the ground marks left behind by a tornado, traveling from left to right (left) and a stationary tornado on corn field (right).

During the 1970s, the author began finding a strange pattern of tree damage in forests. As shown in Fig. 2, trees are blown down in a starburst pattern, as if they were blown out by a jet of descending air as it hits the ground to burst out violently. Structural damage caused by similar outburst winds was also found. Based on his aerial photography, Fujita (1976) postulated the existence of the "downburst", defined as a strong downdraft which induces an outburst of damaging winds on or near the ground. Damaging winds, either straight or curved, are highly divergent. The horizontal extent of outburst winds vary from less than one mile to tens of miles. As reported by West (1979) there had been skepticism on downbursts until 1979.

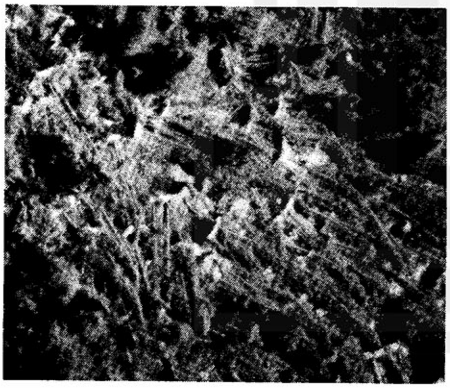
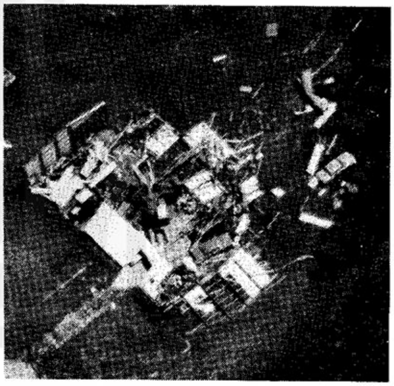

Fig. 2. Aerial views of the damage caused by downburst winds. A starburst pattern of uprooted trees (left) was caused by a microburst which landed near the upper-left corner of the picture. An outbuilding (right) was damaged by microburst winds from lower left to upper right of the picture.

A macroburst is a large downburst with damaging winds extending over 4 km (2.5 miles) and a microburst is a small downburst with damaging wind extending up to 4 km (2.5 miles) horizontally. Due to its small dimension and short life, a microburst is very difficult to detect. Furthermore, the maximum windspeed of microbursts is suspected to be higher than that of macrobursts.

FACT-FINDING OBSERVATION NETWORK

In order to clarify the nature of microburst winds, Fujita and collaborators conducted the following three fact-finding observational projects. They are:

- Northern Illinois Meteorological Research on Downbursts (NIMROD) in 1978,
- Joint Airport Weather Studies (JAWS) in 1982,
- Microburst and Severe Thunderstorm (MIST) in 1986.

Between 27 and 81 ground-based anemometers and up to five Doppler radars were used in measuring the meteorological aspects of all types of microbursts.

Presented in Fig. 3 is a Colorado microburst one minute after the touchdown time. The outflow winds are expanding rapidly from the point of touchdown, picking up dust and debris from the surface. After expanding into 2 to 5 miles in diameter, microburst winds weaken, reaching an insignificant windspeed within 5 to 15 minutes.

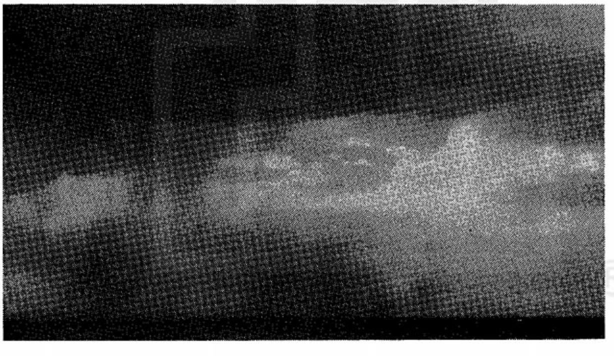

Fig. 3. A microburst on the ground, approximately one minute after the touchdown. Photo by Fujita on July 15, 1981 at Fort Morgan, Colorado.

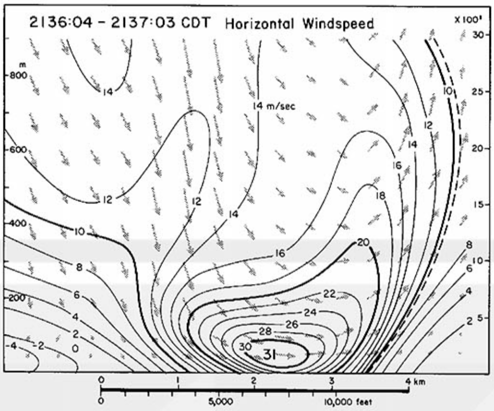

Fig. 4. A vertical cross-section of microburst winds depicted by CP-3 Doppler radar during the NIMROD Project in 1978. Note that the height of the maximum windspeed is only 150' above the ground.

During the NIMROD Project in the western suburbs of Chicago, the CP-3 Doppler radar measured a 69 mph (31 m/s) wind 150' above the ground. Refer to Fig. 4 and Fujita (1985). The CP-3 Doppler radar during the JAWS Project near Denver, CO, successfully sliced a descending microburst as shown in Fig. 5. The microburst shaft was 1,500' in diameter and the splashing echo, 7,000' in diameter.

Fig. 5. A vertical cross-section of microburst shaft and splashing airflow made visible by embedded raindrops as measured by CP-3 Doppler radar during the JAWS Project in 1982.

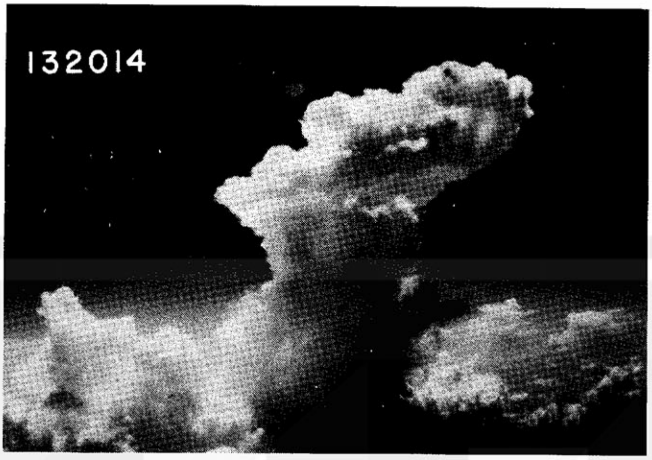

Fig. 6. A small but violent microburst cloud photographed by the author from NOAA's P-3 aircraft at 15,000' MSL during the MIST Project in 1986.

NOAA's hurricane hunter aircraft, P-3, was used in photographing clouds in the microburst stage. A small cloud in Fig. 6 at 13h 20m 14s was inducing strong microburst winds on the ground. Although this storm cloud is very small, the microburst winds from the cloud blew down completely a number of grass fields.

The foregoing three projects revealed three types of microbursts presented in Fig. 7. During JAWS, we often observed strong microburst winds without measurable rainfall on the ground. The cloud base in the MIST Project near Huntsville, AL was very low, accompanied by heavy rain and thunder. However, we found no relationship between rain intensity and windspeed on the ground.

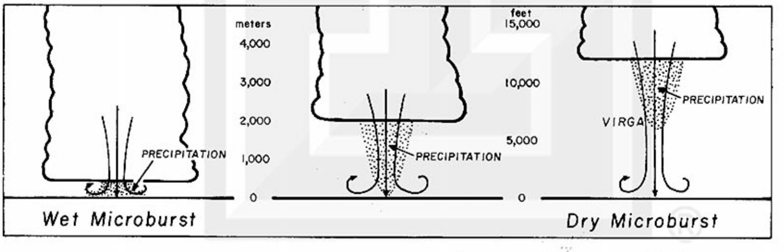

Fig. 7. Three types of microburst clouds confirmed by NIMROD, JAWS, and MIST Projects. Wet microbursts are common in humid areas in the Gulf and East-coast states and dry microbursts, in the western states.

LABORATORY MODEL OF MICROBURST

In a further attempt to study microburst airflow, the author constructed a laboratory model capable of photographing vertical cross sections of microbursts. Figure 8 presents five stages of the microburst airflow. The head of the microburst, made visible by dry-ice smoke, descends toward the surface which has a large

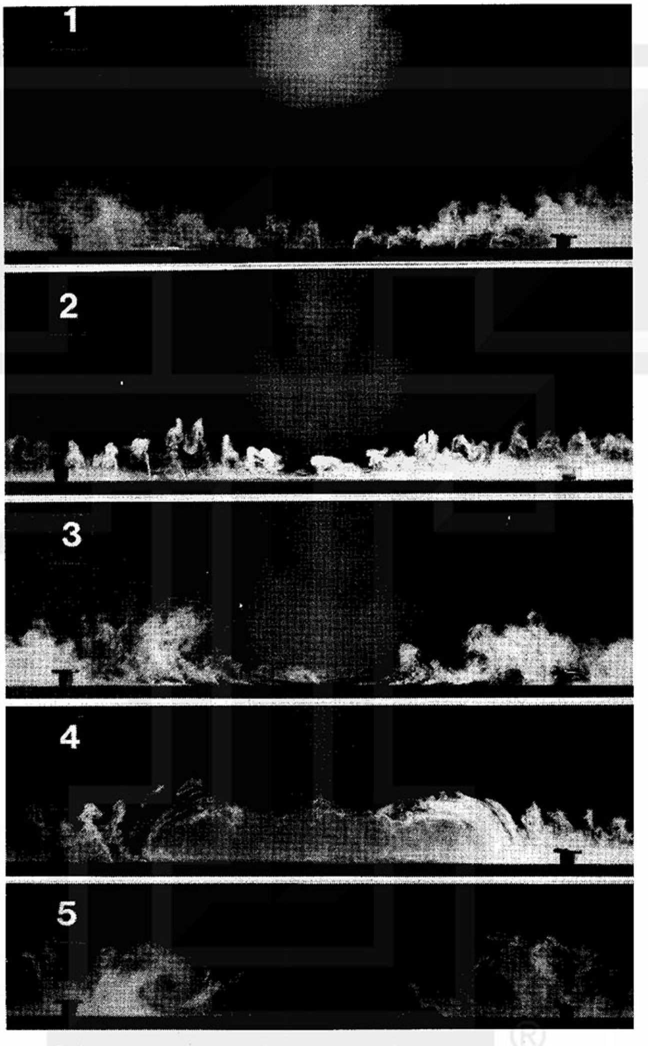

Fig. 8. A laboratory experiment at the Wind Research Laboratory, University of Chicago, showing the evolution of a microburst airflow. In the real atmosphere, this whole process will last only less than two minutes. 1 - Descending Stage, 2 - Contact Stage, 3 - Touchdown Stage, 4 - Spreading Stage, and 5 - Ring-vortex Stage.

number of smoking holes. As the head approaches the surface, the rising smoke is replaced by the descending air. In stage 4, the outburst winds spread, resulting in the formation of a ring vortex. The strongest winds occur directly beneath the vortex axis. This is why the height of the strongest wind is located only 100' to 300'above the ground.

MICROBURST-RELATED AIRCRAFT ACCIDENTS

Jet aircraft is designed to carry heavy weight against the gravitational pull of the earth. The lift force, generated mostly by the main wings, is proportional to the square of the airspeed affecting the wings. Meanwhile, both updraft and downdraft will contribute to an additional rise and sink of an aircraft. Due to a large gross weight, the groundspeed of a large modern aircraft changes gradually. Consequently, an abrupt change in airspeed is caused mainly by the environmental winds. This is why a rapid change in the wind velocity or "wind shear" plays an important role in changing the lift force created by the wings.

So called "low-altitude wind shear" is important because an aircraft at low altitude during approach and takeoff flies at low airspeed of 150 kts or less. A loss of only 30 kts airspeed at such a low airspeed range will reduce the lift force by 36%, resulting in a dangerous sink of the aircraft. Furthermore, an aircraft has no airspace to regain its altitude.

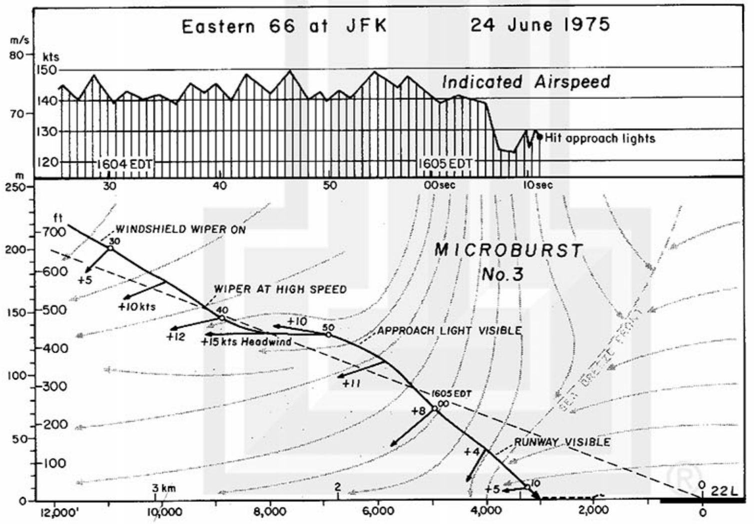

Fig. 9. The first major aircraft accident in microburst at John F. Kennedy Airport, New York City. 112 persons were killed and 12 others were injured.

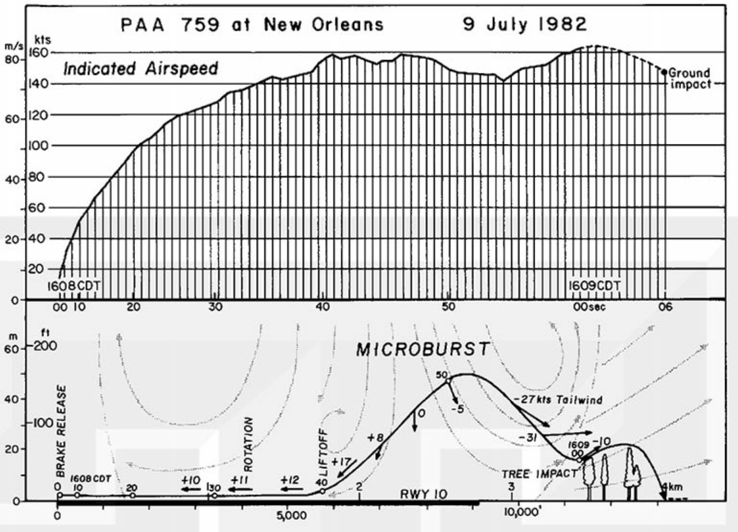

Fig. 10. The second major aircraft accident in microburst at New Orleans Airport. 153 persons were killed and 9 others were injured.

Now, the microburst is identified as an inducer of the most dangerous wind shear. The textbook sequence of the wind shear events during a microburst traverse, if successful, is an increase in headwind before entering the downflow region. During the flyout, an aircraft must penetrate a strong outburst wind or a tailwind. If the tailwind encountered is in excess of 50 kts, the chance of a successful flyout is near zero. Refer to Fujita and Caracena (1977).

Eastern 66 accident in Fig. 9 shows a sequence of the microburst wind shear during the final approach: -- headwind, downflow, loss of headwind, and the ground contact. The Pan American 759 accident in Fig. 10, during takeoff, was caused by a very similar sequence: -- headwind, downflow, 31-kt tailwind, and the tree impact just outside the airport boundary. The third major accident of Delta 191 in Fig. 11 presents an identical sequence of the events: -- 25-kt headwind, 25-kt downflow, 51-kt tailwind, and the ground contact. Refer to Fujita (1986).

An aircraft in a microburst will traverse through a predictable sequence of the wind shear which can be identified by an experienced pilot trained by simulators with microburst winds. It is expected that microburst-related accidents will decrease with an increasing knowledge and training of airline pilots, along with the development of the microburst-detection technology.

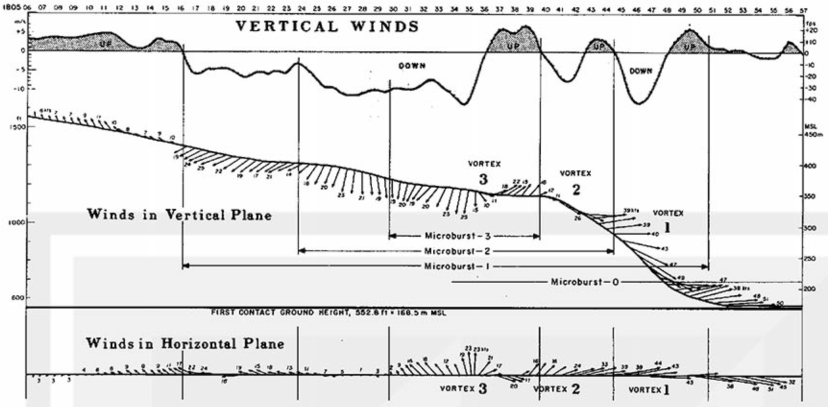

Fig. 11. The third major aircraft accident in microburst at Dallas-Ft. Worth Airport on August 2, 1985. 137 persons were killed. Winds in both vertical and horizontal planes were determined from the digital flight data recorder (DFDR) readout.

MAXIMUM WINDSPEEDS OF MICROBURST

An aircraft accident in a microburst could occur when the tailwind speed is far below that which could cause structural damage. With low probabilities, however, microburst winds are expected to be high enough to be a concern by structural engineers.

The highest windspeed ever recorded in microbursts hit the top scale of 149.7 mph (130 kts). The wind trace in Fig. 12 was recorded by a propeller anemometer at 16' above the Andrews Air Force Base runway on August 1, 1983. The peak wind from the northwest occurred at 14h 10m 45s EDT, followed by only a 2-kt wind when the dead center of the microburst passed directly over the anemometer some two minutes later. At 14h 13m 40s EDT, an 84-kt wind came from the southeast, the direction opposite from the first peak wind. President Reagan, returning from Atlanta on Air Force One, landed at 14h 04m EDT, approximately six minutes in advance of the peak microburst wind.

After studying a sequence of microbursts in Michigan, Fujita and Wakimoto (1981) found a 390-lb chimney which flew through a distance of 350' (105 m) over a single-story house on the other side of a highway. Between 112 and 123 mph windspeeds were estimated on the basis of ballistic analysis. They also reported that the microburst wind uprooted a one-ton corn storage which became airborne through a distance of 530' (163 m) and rolled 1,940' (590 m) across a field before hitting trees in a forest.

Similar to the tornado windspeed, microburst windspeed should be expressed by a function of per year probability. Windspeed statistics from NIMROD and JAWS anemometers in Fig. 13 reveal the 145 mph and 130 mph windspeeds, respectively, with a 10^{-5}

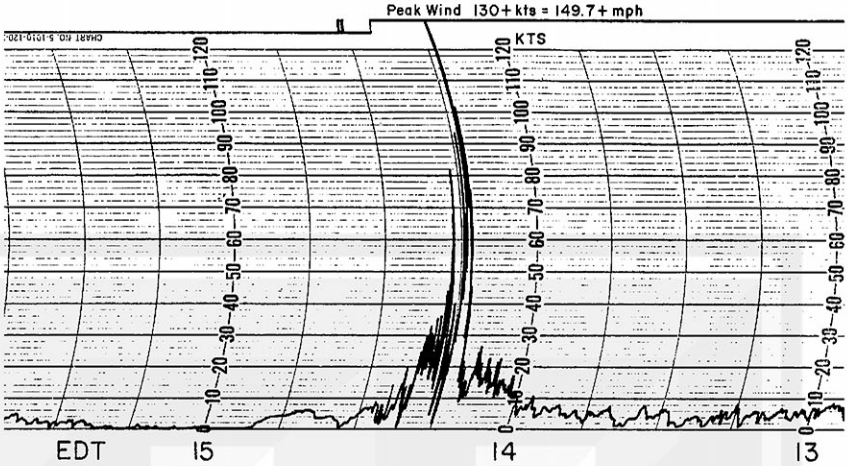

Fig. 12. Andrews Air Force Base microburst on August 1, 1983. The peak wind of 149.7 mph at the top scale was the highest wind-speed ever recorded in microbursts in the United States.

per year probability. These windspeeds are less than the tornado windspeeds with a comparable probability. Because of higher frequencies and large individual area of a microburst, probabilities of structural damage by microbursts with 50 to 100 mph range of windspeeds could be much higher than those of tornadoes.

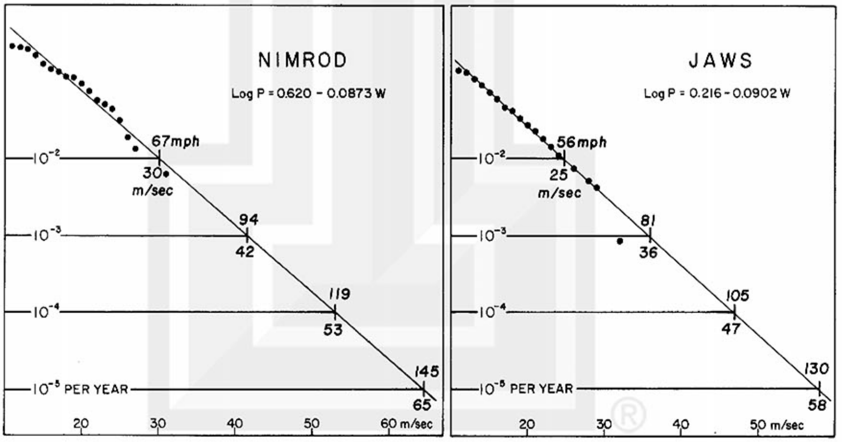

Fig. 13. Microburst windspeeds in the NIMROD and JAWS Projects plotted as functions of the occurrence probability per year. These diagrams suggest that some of the damage by tornado could have been caused by strong microburst.

CONCLUSIONS AND ACKNOWLEDGEMENT

Tornadoes have been known to us over 100 years and their statistical records have been accumulated since 1916. During the 72-year period, 1916 through 1987, a total of 32,541 tornadoes were confirmed in the continental United States. Because the tornado damage is well-known to the general public, most of the damage in the wake of a high peak-wind has been attributed to a tornado.

In spite of the fact that microbursts in recent years became popular in the aviation community, little attention has been paid to the damaging winds until the Houston area was hit by both tornadoes and downbursts on May 20, 1983. A post-storm survey of the Houston area damage made by the University of Chicago team revealed that 5 persons were killed by 8 tornadoes in the 6 square mile area and 6 persons were killed by the 9 downbursts covering an amazingly large area of 1,040 square miles.

Recent studies revealed the evidence that intense microburst winds could be induced by relatively small, innocuous clouds, and there is a suspicion that some of the shipwrecks in the Bermuda Triangle could have been caused by the microburst winds over the Gulf Stream. It is expected that the engineering community will pay attention to the new type of downburst winds in assessing the structural damage in the wake of an abrupt peak wind.

The research presented in this paper has been sponsored by the National Science Foundation under Grant ATM85-16705 and NESDIS under Grant NA85AADRA064.

REFERENCES

Byers, H.R.; and Braham, Jr., R.R., "The Thunderstorm", Government Printing Office, Washington, D.C., 287 pp., Jun., 1949.

Fujita, T.T., "Spearhead Echo and Downburst near the Approach End of a John F. Kennedy Runway, New York City", SMRP Research Paper, University of Chicago, No. 137, 51 pp., Mar., 1976.

Fujita, T.T., "THE DOWNBURST: Microburst and Macroburst", SMRP Research Paper, University of Chicago, No. 210, 122 pp., [NTIS PB85-148880], Feb., 1985.

Fujita, T.T., "DFW Microburst on August 2, 1985", SMRP Research Paper, University of Chicago, No. 217, 154 pp., [NTIS PB86-131638], Jan., 1986.

Fujita, T.T.; and Caracena, F., "An Analysis of Three Weather-Related Aircraft Accidents", Bulletin of American Meteorological Society, Vol. 58, No. 11, pp. 1164-1181, Nov., 1977.

Fujita, T.T.; and Wakimoto, R.M., "Five Scales of Airflow Associated with a Series of Downbursts on 16 July 1980", Monthly Weather Review, Vol. 109, No. 7, pp. 1438-1456, Jul., 1981.

West, S., "Are Downbursts just a Lot of Hot Air?", Science News, Vol. 115, pp. 170-171, Mar., 1979.